THE BEHAVIOUR OF BUCKLING RESTRAINED BRACE (BRB) SYSTEM AT ELEVATED TEMPERATURE

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requirements for the award of the degree of
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I dedicate with love and gratitude

to my mother, father, husband and mother in-law

for being with me till the very end of my thesis completion.

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ABSTRACT

Buckling Restrained Braces (BRB) have been widely used in the construction industry as they utilize the most desirable properties of both constituent materials, i.e., steel and concrete. They present excellent structural behaviours such as high load bearing capacity, ductility, energy-absorption capability and good structural fire behaviour. In this study, the use of BRB systems on enhancing the fire resistance of whole building in terms of preventing the progressive collapse of the structural frame against fire was investigated. The effect of size and type of filler material of existed gap at the steel core-concrete interface as well as the element's cross sectional shape on the fire resistance of BRB isolated member was explored. The accuracy of numerical solution was certified by comparing the FE results with those of analytical formulations and experimental predictions. The study in this thesis shows that the superior fire performance of BRB can be obtained by altering the filler material of the gap from metal to concrete as well as by increasing the size of the gap. Also, cylindrical cross-section BRB perform better under fire conditions compared to that of rectangular cross section. In terms of verifying the efficiency of BRBs in preventing the progressive collapse of the structural frame under fire, a new framework called "stiffness reduction" technique was proposed and the response of BRBs was compared with that of Ordinary Concentrically Brace systems (OCBs). The results indicate that BRBs provide higher global collapse temperature of the frame, owing to the greater stiffness they append to the structural frame as compared to OCBs. Moreover, BRBs are strength enough to distribute the sustained load by heated columns to the adjacent members without any buckling occurrence in the bracing member, maintaining the stability of whole frame for a longer period of heating time through both heating and cooling phases of fire.

ABSTRAK

Lengkokan dihalang Penyokong (BRB) telah digunakan secara meluas dalam industri pembinaan kerana mereka menggunakan ciri-ciri yang paling diingini dari kedua-dua bahan konstituen, iaitu keluli dan konkrit. Mereka membentangkan tingkah laku struktur yang sangat baik seperti keupayaan galas beban yang tinggi, kemuluran, keupayaan tenaga penyerapan dan tingkah laku kebakaran struktur yang baik. Dalam kajian ini, penggunaan sistem BRB bagi meningkatkan ketahanan api bangunan keseluruhan dari segi mencegah keruntuhan progresif bingkai struktur terhadap kebakaran telah dikaji. Kesan saiz dan jenis bahan pengisi bagi jurang wujud yang pada muka teras konkrit keluli serta bentuk keratan rentas elemen pada ketahanan api daripada BRB ahli terpencil telah diterokai. Ketepatan penyelesaian berangka telah disahkan dengan membandingkan hasil FE dengan rumusan analisis dan ramalan eksperimen. Kajian dalam tesis ini menunjukkan bahawa prestasi api ke atas BRB boleh diperolehi dengan mengubah bahan pengisi jurang dari logam untuk konkrit dan juga dengan meningkatkan saiz jurang. Juga, keratan silinder BRB berprestasi lebih baik di bawah keadaan kebakaran berbanding dengan keratan rentas segi empat tepat. Dari segi mengesahkan kecekapan BRBs dalam mencegah keruntuhan progresif bingkai struktur di bawah api, satu rangka kerja baru yang dikenali sebagai teknik "pengurangan kekukuhan" adalah dicadangkan dan tindakbalas BRBs telah dibandingkan dengan sistem sepusat kekangan biasa (OCBs). Keputusan menunjukkan bahawa BRBs menyediakan suhu keruntuhan global yang lebih tinggi daripada bingkai biasa, kerana kekukuhan yang lebih besar yang diperolehi mereka kepada bingkai struktur berbanding OCBs. Selain itu, BRBs mempunyai kekuatan yang mencukupi untuk mengagihkan beban yang berterusan pada tiang-tiang yang dipanaskan kepada ahli-ahli bersebelahan tanpa apa-apa kejadian lengkokan dalam anggota perembatan dan mengekalkan kestabilan keseluruhan rangka untuk tempoh yang lebih lama melalui kedua-dua fasa pemanasan dan penyejukan api.

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LIST OF ABBREVIATIONS

AISC	-	American Institute of Steel Construction
BRBF	-	BRB frame
BRBs	-	Buckling restrained brace system
BRE	-	Building Research Establishment
BS	-	British Steel
CDP	-	Concrete damaged plasticity
CFDST	-	Concrete filled double skin tubular
CFT	-	Concrete filled steel tube
CHS	-	Circular hollow sections
CP	-	Collapse Prevention
EC	-	Euro code
EHS	-	Elliptical hollow sections
FE	-	Finite element
FEMA	-	Federal Emergency Management Agency
FRR	-	Fire resistances rating
GF	-	Green’s function
HSC	-	High strength concrete
ICC	-	International Code Council
IMPA	-	Improved modal pushover analysis
IO	-	Immediate Occupancy
ISO	-	International Standards Organization
LS	-	Life Safety
MFIAJ	-	Marine and Fire Insurance Association of Japan
MPA	-	Modal pushover analysis
MPP	-	Mass proportional pushover

MRF	-	Moment resisting frame
MRs	-	Moment resisting system
NSC	-	Normal strength concrete
OCBs	-	Ordinary concentric brace system
PBPD	-	Performance-based plastic design
RHS	-	Rectangular hollow sections
SCC	-	Self-consolidating concrete
SHS	-	Square hollow sections
SMR	-	Special moment resisting
T-t	-	Temperature-time
3D	-	Three dimensional
2D	-	Two dimensional
1D	-	One dimensional

LIST OF SYMBOLS

ε_{total}	-	Total strain
$\varepsilon_{thermal}$	-	Thermal strain
$\varepsilon_{mechanical}$	-	Mechanical strain
δ	-	Overall deformed shape
α	-	Coefficient of thermal expansion
ΔT	-	Temperature rise
E	-	Module of elasticity
A	-	Cross-section area
σ_a	-	Axial stress
σ_y	-	Yield stress
ΔT_y	-	Yield temperature
P_{cr}	-	Buckling load
l	-	Length of element
I	-	Moment of inertia
λ	-	Slenderness ratio
K_t	-	Spring stiffness
$f_{r,t}$	-	Steel tube radial stress
$f_{\theta,t}$	-	Steel tube tangential stress
$f_{z,t}$	-	Steel tube axial stress

$f_{r,c}$	-	In-filled concrete radial stress
$f_{\theta,c}$	-	In-filled concrete tangential stress
$f_{z,c}$	-	In-filled concrete axial stress
$f_{r,co}$	-	Steel core radial stress
$f_{\theta,co}$	-	Steel core tangential stress
$f_{z,co}$	-	Steel core axial stress
T_t	-	Steel tube thickness
D_t	-	Steel tube diameter
$\varepsilon_{r,t}$	-	Steel tube radial strain
$\varepsilon_{\theta,t}$	-	Steel tube tangential strain
$\varepsilon_{z,t}$	-	Steel tube axial strain
$\varepsilon_{r,c}$	-	In-filled concrete radial strain
$\varepsilon_{\theta,c}$	-	In-filled concrete tangential strain
$\varepsilon_{z,c}$	-	In-filled concrete axial strain
$\varepsilon_{r,co}$	-	Steel core radial strain
$\varepsilon_{\theta,co}$	-	Steel core tangential strain
$\varepsilon_{z,co}$	-	Steel core axial strain
υ	-	Poisson's ratio
ε_{oct}	-	Octahedral normal strain
γ_{oct}	-	Octahedral shear strain
σ_{oct}	-	Octahedral normal stress
τ_{oct}	-	Octahedral shear stress
K_c	-	In-filled concrete bulk modulus
G_c	-	In-filled concrete shear modulus

$f_{B,c}$	-	In-filled concrete compressive strength
γ_c	-	In-filled concrete unit weight
r_0	-	Steel core radius of cylindrical BRB element
r_1	-	In-filled concrete radius of cylindrical BRB element
r_2	-	Steel casing radius of cylindrical BRB element
α_c	-	Thermal diffusivity of in-filled concrete
C_c	-	Thermal conductivity of in-filled concrete
T_i	-	Initial (ambient) temperature
T_g	-	Temperature at fire interface
T_s	-	Steel casing temperature
$q_1(t)$	-	Ingoing heat flux
σ	-	Stefan-Boltzmann constant
ε	-	Emissivity of radiation process
h_v	-	Coefficient of convective heat transfer
$q_2(t)$	-	Heat flux at the steel tube-concrete interface
Q_s	-	Lumped heat capacitance of the steel tube casing
$J_n(z)$	-	Bessel function of the first kind of order *n*
ζ_n	-	Positive roots of the transcendental equation
θ_s	-	Steel material temperature
$f_{c,\theta}$	-	Concrete material elevated temperature strength
θ_c	-	Concrete material temperature
$q_{convection}$	-	Convection heat flux
$q_{radiation}$	-	Radiation heat flux
T_f	-	Temperature of fire furnace
T_o	-	Absolute zero temperature

ε_f	-	Emissivity of fire
ε_m	-	Emissivity of steel surface

CHAPTER 1

INTRODUCTION

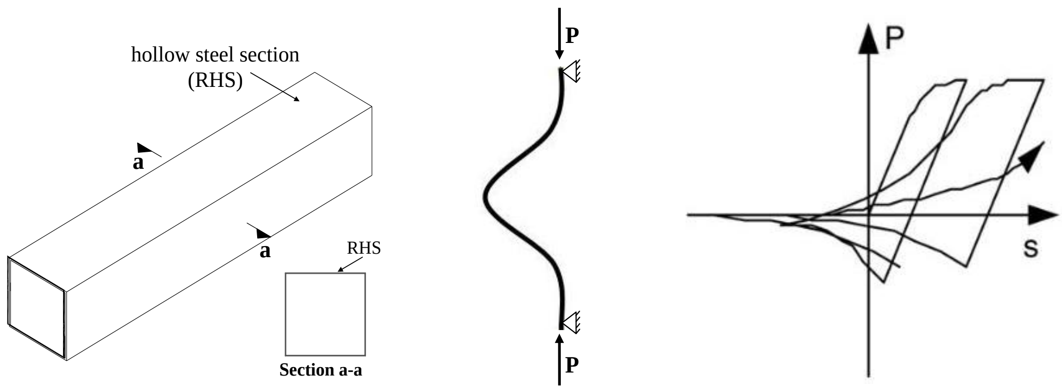
1.1 General

1.1.1 Overview of Fire Hazard

Fire event is one of the most hazardous conditions that any building could encounter throughout its service life. If buildings are not appropriately designed and constructed, this disaster could produce huge obliteration in terms of loss of life, property and money. With increasing interest in developing large cities as well as constructing huge structures with multiple stories, which involve a large amount of combustible furniture, the probability of fire hazard becomes higher. Moreover, severe earthquakes in urban regions are frequently followed by major conflagrations, which are hard to control and leads to huge destructions (e.g. 1995 Kobe earthquake). When a fire happens in the structure, temperature rise due to fire event can lead to the reduction in material strength, which then causes decrease in the strength and stiffness of the structural load bearing elements. It can also induce a big thermal axial forces as well as deformations in the structural members. These two phenomena are the main reason of structural collapse during fire. Therefore, fire concept and gaining a thorough understanding of the vulnerability of structures under fire conditions impose significant challenges to the structural engineering community in recent years.

1.1.2 Overview of Ordinary Brace systems

Lateral displacements of the buildings against various loading conditions have subjected significant challenges to the structural engineering community. In order to decrease these displacements, which are mainly resulted from the wind and earthquake forces, horizontal bracing systems are formed and appended to the structural frames. In the conventional systems, when the bracing elements are subjected to the big axial forces the buckling occurs in the corresponding members as shown in Figure 1.1(a), which is then followed by the failure of bracing components. Consequently, the capacity of ordinary bracing members is significantly limited under compression, owing to the occurrence of buckling before reaching the load level that corresponds to the plastic response. Therefore, such these members are considered in design as tension-only braces and not used to their full capacity. Figure 1.1(b) shows the hysteretic response of ordinary bracing systems, in which the unsymmetrical behaviour is resulted from the buckling of bracing members beneath compression force.

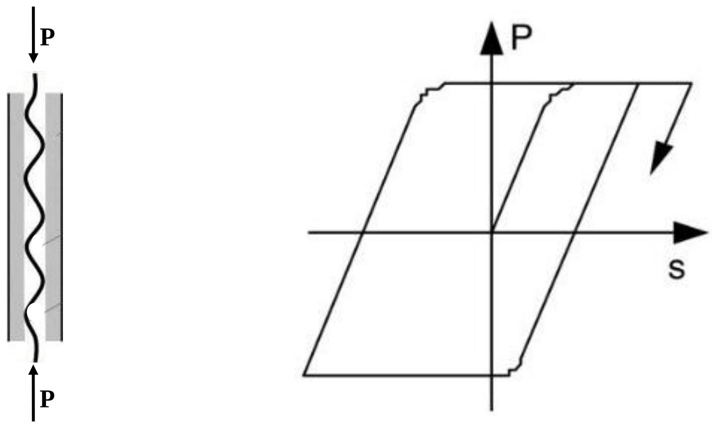


(a) (b) (c)

Figure 1.1 (a) Typical section of ordinary bracing (OCB) element, (b) the behaviour of OCB against axial loading, (c) the hysteretic response of conventional bracing systems (Xie, 2004)

1.1.3 Overview of Buckling Restrained Brace systems (BRBs)

As mentioned in Section 1.1.2, the conventional bracing members buckle under compression force. In order to overcome this negative characteristic of ordinary braces, the overall buckling of bracing element should be prevented such that the tensile and especially compressive components are capable of sustaining higher axial forces. This requirement stimulates researchers to conduct an improved type of bracing system called the buckling restrained brace (BRB), as demonstrated in Figure 1.2 (a). The un-buckled characteristic of BRBs leads to a similar tension and compression behaviour of bracing components at the hysteretic loop, as shown in Figure 1.2 (b).



(a) (b)

Figure 1.2 (a) The behaviour of BRB element under axial loading, and (b) the hysteretic response of BRB system (Xie, 2004)

Attributing to the superior performance of BRBs as restraining system due to their high potential of distributing axial loadings without the occurrence of buckling in the bracing members, BRBs are found to decrease noticeably the lateral displacements of the structural frame in comparison to the ordinary types as shown in Figure 1.3.

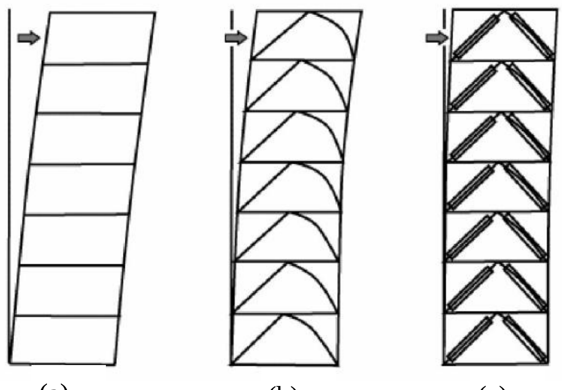


Figure 1.3 Comparison of storey drift demand for the structural frame (a) without braced resisting system, (b) with ordinary bracing system, and (c) with BRB system (Mack and Chenault, 2007)

The use of BRBs has been extensive in recent decades owing to their supreme structural behaviour in terms of enhancement of lateral resistance of the structural frames against earthquakes. The efficiency of using this system under static and seismic loadings at ambient temperature had been well studied and documented (Clark et al., 1999; Uang and Nakashima, 2004; Kigginsa and Uang, 2006; Newell et al., 2006; Sahoo and Chao, 2010).

The principal strong specifications of BRB systems are high energy dissipation capability, high ductility and almost symmetrical hysteretic responses in tension and compression (Sahoo and Chao, 2010). As shown in Figure 1.4 (a), BRB components are consisted of a steel core encased in a concrete-filled steel hollow (CFT) casing for an enhanced buckling resistance. In terms of its constituents, the steel core is composed of a yielding steel core, non-yielding and buckling-restrained transition parts, non-yielding and unrestrained end regions (Figure 1.4 (b)). About 60%-70% of the entire length of the core is restrained by the casing (Sahoo and Chao, 2010). In these bracing systems, compression stresses are mainly sustained by the restrained portion of the core. On the other hand, the yield strength of the steel core is much lower than that of steel tube casing. This allows the core to yield in the same manner during tension and compression prior to the casing, thus considerably enhancing the energy dissipation capabilities of BRBs in comparison to the ordinary bracing systems. Due to the Poisson's effect on the steel core, it expands when it is compressed. To prevent the axial stress transition from the core to the restrainer (in-filled concrete steel tube casing), a certain amount of clearance between the core and concrete must be provided to avoid the friction between them (Figure 1.4(c)).

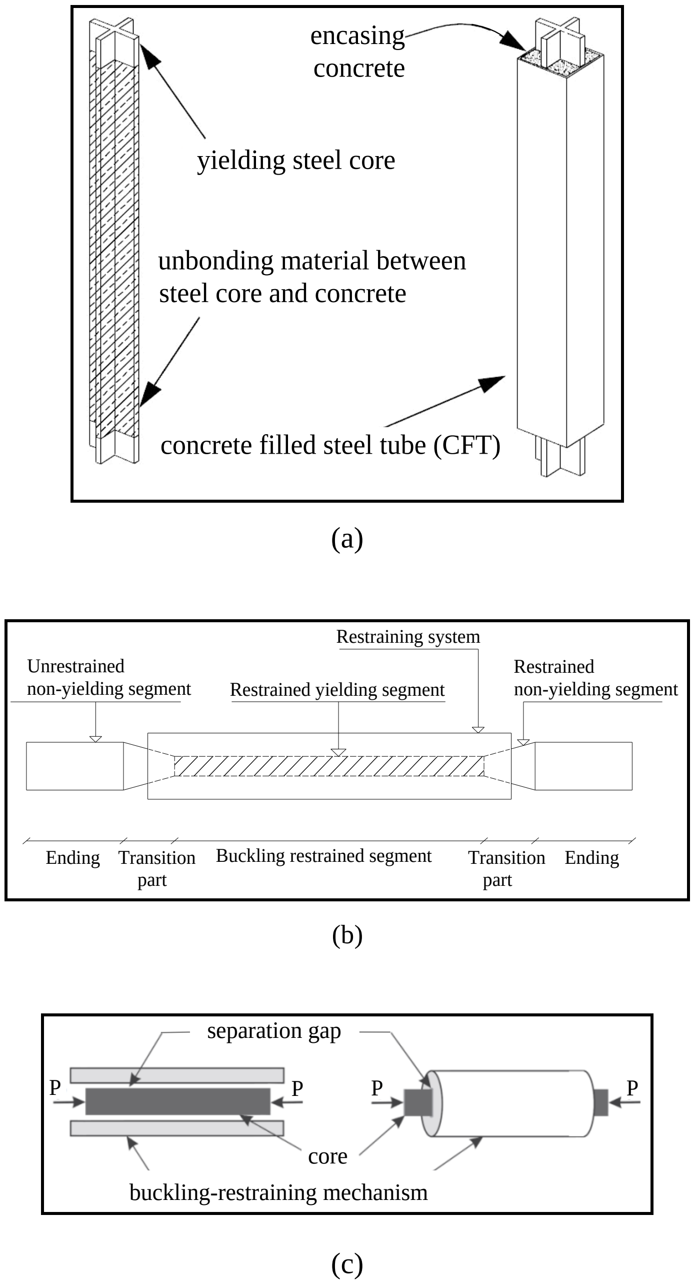


Figure 1.4 Detail of BRB (a) general structure (Clark et al., 1999), (b) steel core constituent segments and (c) separation gap at steel core-restrainer interface (Korzekwa and Tremblay, 2009)

In addition to this gap, in order to almost completely minimize the friction between the core and concrete, a de-bonding agent is also applied to the surface of the core, as shown in Figure 1.4(a).

1.2 Background of the Problem

Traditionally, the preliminary building fire-design codes prepare provisions based on a perspective approach, considering some basic parameters such as the location and number of sprinklers, fire alarms, smoke detectors and exits, which necessitate the structures to meet the relevant standard rules in terms of fire safety concept. However, several studies had demonstrated that such active fire protection systems were easily damaged at fire, and their operational mechanisms were disturbed due to their mechanical failure and deformations (MFIAJ, 1995). This has led to the widespread application of passive fire protection systems in the form of sprays, boars and intumescent onto the surfaces of structural elements, to get the assurance that their temperatures remain lower than the critical value during heating stages. In regards to this, concrete has been known commonly as a safe material, owing to its low conductivity and large thermal inertia (Buchnanan, 2001). Conversely, steel is considered to be more vulnerable to fail beneath heating, because of its high conductivity and small thermal inertia such that it is usually coated by fire protective materials. In terms of economy, previous surveys (Robinson and Latham, 1986; Lawson and Newman, 1990; Lawson, 2001) have recorded that using such fire protection systems increase the total cost of the structure by more than 30%. The increase in the constructional charge of buildings has drawn the attention of engineers to explore the use of various alternative fire resistance techniques.

One of the operational solutions for this problem has been recognized as the enhanced strength and stiffness of the structural frame that prevents progressive collapse from local to global for life safety against fire, i.e., allowing the occupants to leave the building before the overall failure of structure at fire. In this case, in order to certify and monitor the stability of the structure at fire, the performance-based approach, (Eurocode 2-4, 2005) which represents the progression of actual heating stages in the structural frame while it is subjected to fire, has been extended.

To date researchers implemented the performance-based technique in the form of laboratory fire tests on the individual structural elements. As a result, structural engineers have used these test results extensively, without considering how trustworthy they are, by not taking into account whether the corresponding data represent the actual behaviour of the whole structure or not. On the other hand, it has been proven for many years that the elevated temperature behaviour of entire building is completely different from that of isolated element, beneath fire loading (Baily et al., 1999; Usmani et al., 2005; Wald et al., 2006-2007). In order to track the real response of a structural frame (with actual boundary conditions) at fire, full scale fire tests need to be conducted on the whole structure and the structural fire design has to be carried out by the performance-based design of the entire building. Conducting such a large-scaled set of fire tests has been extremely complex, expensive, and engaged major risks in a controlled environmental condition. Moreover, with the advancements in the computational technology, computer models have shown that they are capable enough to simulate and analyze the real states of structures at fire with acceptable accuracy. Hence, finite element (FE) programs can be good alternatives to model the large scale parametric studies on fire. Consequently, from the early 2000's the use of FE programs has been expanded extensively for evaluating the response of whole building during fire, instead of conducting full scale fire tests. Subsequently, various FE programs such as SAFIR (Chitty and Foster, 2001; Lim et al., 2004; Vila Real et al., 2004; Pyl et al., 2012) has been used to simulate the real fire exposure numerically. Also, the use of FE package, ABAQUS, has been extended by British Steel and many other researchers (Sanad, 1999 and 2000a-d; Gillie, 2000; Sun et al., 2012a; Agarwal and Varma, 2014), owing to its capability of simulating both material and geometric nonlinearities in the structural frame during fire. Recently, the application of other FE program, VULCAN, has been developed (Najjar and Burgess, 1996; Huang et al., 2009; Huang, 2010-2011; Yu et al., 2011; Sun et al., 2012b) at the University of Sheffield as a specific FE tool for monitoring the elevated temperature behaviour of structures at fire. The use of these FE programs has prepared a comprehensive perspective of how the structural load bearing members as well as the whole building perform at high temperatures under fire condition.

1.3 Statement of the Problem

In order to know the level of resistance in the buildings against fire loading, the elevated temperature behaviour of structural frame, considering different horizontal resisting systems needs to be investigated. While there have been extensive advances in the consideration of structural behaviour at fire in recent decades, there are still many aspects of structural-fire responses that are not well understood and need further studies. For instance, no study has yet been done on the fire resistance of multi storey structures with Buckling Restrained Brace system (BRBs). Therefore, supplementary research is required to observe the performance and influence of this type of bracing system on the overall stability and resistance of an entire structure toward fire hazard.

The research work carried out in this thesis is hoped to shed light on the performance of multi-storey buildings with BRBs under fire condition. The research considered the elevated temperature behaviour of BRB constituent components as an individual member subjected to fire loading, as well as the study on the influence of this type of bracing system on the fire resistance of entire building. The outcome of this research is very useful for the future design considerations on the fire resistance of multi-storey structures restrained with BRB system. Generally, the overall problems of this study are identified as follows:

1. Unknown elevated temperature performance of BRB individual element (sub-element) under fire loading with respect to the reduction in material strength due to temperature rise, under fire conditions need to be addressed.

2. Unknown BRB system effect on the overall stability and resistance of entire building against fire loading need to be established.

3. How correct is the current nonlinear finite element (FE) analysis to perform the actual behaviour of structural frame with BRBs subjected to fire need to be validated.

1.4 Objectives of the Study

This thesis concentrates on the behaviour of BRB individual element at high temperatures as well as the additional strength provided by this system on the fire resistance of the structures with multi-storey frames. In order to accomplish the main aim of this study, the objectives of this research can be specified as follows:

1. To develop an efficient three dimensional (3D) numerical modelling for investigating the nonlinear behaviour of BRB constituent components under fire loading and validating the numerical approach with the existing analytical formulations and experimental test results.

2. To develop an efficient two dimensional (2D) numerical modelling in order to recognize the influence of BRB system on preventing the progressive collapse of structural plane frame against fire loading, using the proposed technique to simulate the global collapse of the structural frame at fire.

3. To develop an efficient 3D numerical modelling for investigating the effect of BRBs on the fire resistance of whole building and validating the accuracy of

the proposed model by comparing the FE results with the existing full scale fire tests (Cardington fire test).

4. To compare the efficacy of BRBs on enhancing the overall stability and fire resistance of whole building resulted from objectives 3 and 4 with that of ordinary concentrically bracing system (OCBs).

1.5 Significance of the Study

In last decades, the extensive developments in urbanizations have led to an enhancement in the potential of fire fatalness in different types of buildings. Fire can be a major catastrophe to the safety of building industry. Strength and stiffness of structural load bearing elements will reduce dramatically at elevated temperatures. On the other hand, high temperatures will induce large axial forces and big deformations in the structural members, causing by the global collapse of the whole building due to fire.

Now-a-days, steel constructions have a great consumes acceptability due to their advantages in the building industry all over the world. The possibility of reducing the cross section area of the structural elements, the ability of building such structures more rapidly and the advantages of light weight steel structures contribute to the tendency of structural engineers to prefer steel as construction material rather than the other construction materials. However, steel mechanical properties are very vulnerable at elevated temperature. In addition to its high conductivity, reduction in material strength at high temperatures is another negative characteristic of steel. Recently, in order to improve the poor performance of steel structures at elevated temperature, some provisions such as protecting the steel structural members or alternative design methods have been developed under fire conditions.

Despite of significant researches that have been done to understand the elevated temperature behaviour of buildings at fire incidents in recent decade, there are still many relevant areas of interest that are not well understood and require additional research. As an example, the efficiency of using BRB system under static and seismic loadings at ambient temperature had been well studied and documented (Clark, 1999; Uang, 2004; Sahoo, 2010). However, only limited literatures (Saitoh et al., 2005; Talebi et al, 2014a-c) had explored its performance in fire situation. So, there is a lack of understanding on the structural behaviour of such braces at elevated temperatures.

The investigation presented in this dissertation is intended to contribute to improve the structural behaviour of steel frames restrained with BRB systems under fire conditions.

1.6 Research Findings/Expected Outcomes

There are three expected outcomes in this study. First, the performance of BRB sub-element (isolated member) against fire loading can be predicted such that whether the elevated temperature behaviour of BRB is analogous to that of normal temperature (20 °C), i.e., steel core yields prior to the restraining system due to thermal loading. Second, the effect of BRB system on the overall stability and resistance of a multi-storey building subjected to fire in contrast to that of OCBs and third, the effectiveness of finite element analysis to represent the actual performance of a structure with BRBs exposed to fire hazard.

1.7 Scope of the Study

This research study provides a theoretical basis to understand further high-temperature structural properties and refractory limit of BRBs when exposed to fire. By means of this research, the performance of BRB element in incidents of fire caused by earthquakes and situations of fire without the axial seismic force are investigated and validated analytically in the elastic domain. Also, this study reveals the positive and negative remarks of using BRB system instead of OCBs to resist the structural collapse under fire conditions. Finally, this research work provides useful information to the structural engineers on how to use finite element analysis to predict the failure of building and thus increase the structural safety under fire conditions.

1.8 Research Methodology

Research methodology is a guideline to carry out the study in an organized manner so as to attain the research objectives. In this thesis, the research procedure mainly contains of 3 stages as shown in Figure 1.5, namely, "Stage A": Primary study on elevated temperature behaviour of BRB isolated element, "Stage B": Secondary study on the performance of BRB system on a 2D plane frame at fire, "Stage C": Ultimate study on the response of BRB system on a 3D structure under fire condition. The process of research and the approaches of analyses used are as follows:

- Stage A: includes a primary study on the behaviour of an individual BRB element under fire condition. In this phase of study, coupled nonlinear thermal-stress analysis was conducted, using ABAQUS package. In the primary study, the responses of each constituent components of BRB at elevated temperatures were verified and concluded. The accuracy of numerical approach was validated by the existing analytical studies as well as experimental tests. At the end of this stage, the elevated temperature behaviour of BRB sub-element was concluded.

- Stage B: involves the performance of BRB system on a plane frame under fire condition. In this part of study, a two dimensional analysis was conducted, using VULCAN program. In this step, the influence of BRB system on the progressive collapse prevention of the structural frame due to fire loading was investigated and its response was compared with that of OCBs. The outcomes at this stage of research gives a comprehensive scheme on the influence of BRB system in transferring the load from the buckled-heated columns to the unheated stiffer members, which was followed by the prevention of spreading the local to global collapse of structural frame at fire, compared to OCBs. The accuracy of FE results was verified with the existing parametric work on the performance of ordinary systems at fire.

- Stage C: consists the response of BRB system on the resistance of whole building under fire scenario. In this stage of study, a three dimensional model was conducted, using ABAQUS package. The effect of using BRB system on the overall stability and resistance of a multi-storey structure exposed to fire was investigated in this stage. This concluding stage of research proposed a comprehensive solution on the use of BRB system as compared to that of OCBs in enhancing the fire resistance of the structures with multiple stories. The accuracy of the proposed numerical model results was validated with the predictions of existing experimental fire test carried out on an eight storey building at Cardington laboratory (Lennon, 1997).

These three stages explained the general scheme of the research methodology that has been implemented in this study. A thorough description on each stage is detailed out in Chapters 4 to 6. Finally, the thesis is ended with concluding remarks and recommendations for future studies.

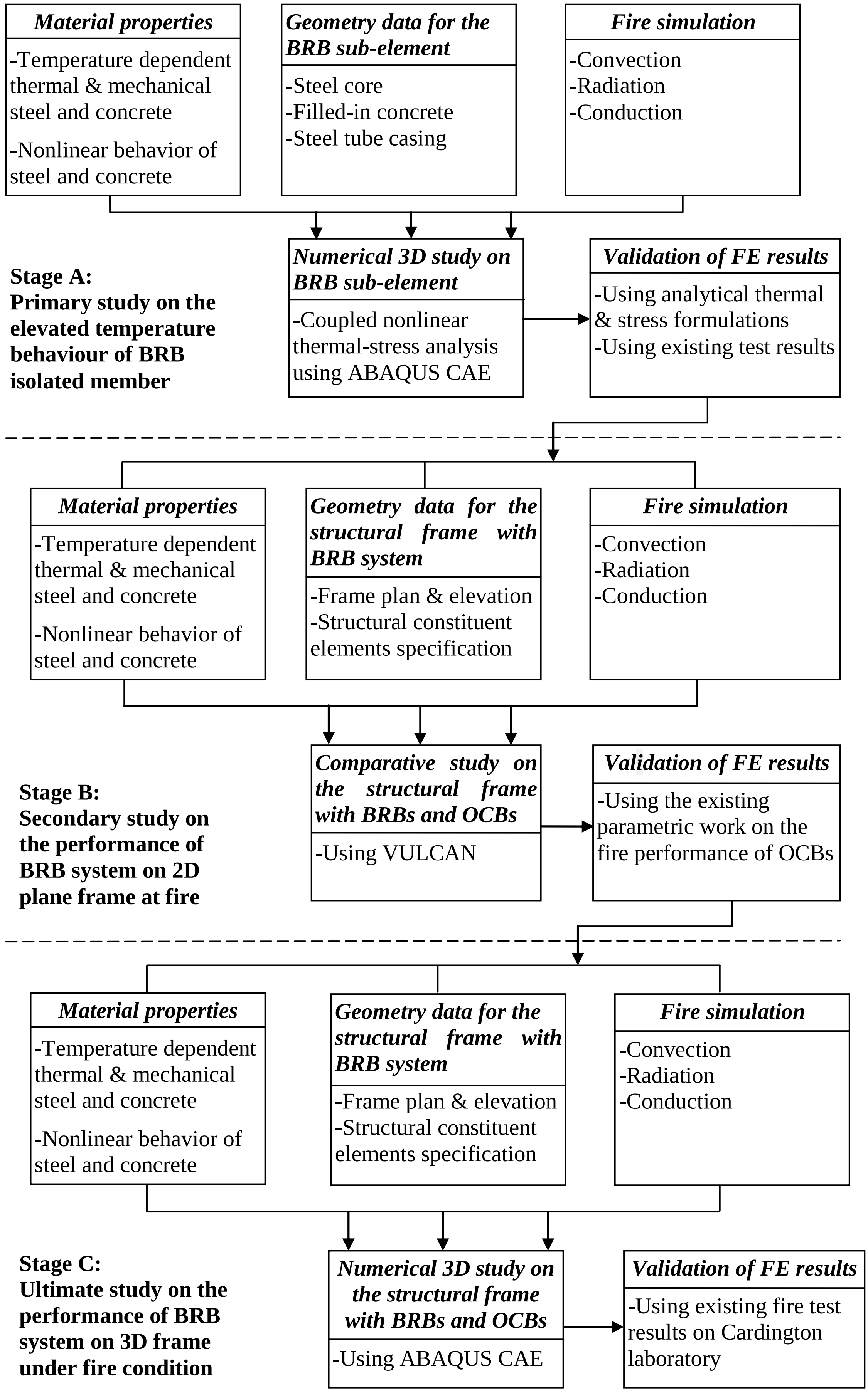


Figure 1.5 Research methodology

1.9 Thesis Organization

This thesis comprises seven chapters, which are arranged according to the sequence of the main objectives and rationale of the study. A brief description on the structure of these seven chapters is provided below.

- ***Chapter 1: Introduction.*** This is the current chapter which formulates the research proposal and describes the background of the study, statement of the problem, objective of the study, significant of study, research findings and expected outcomes, scope and limitations, research methodology and thesis organization.

- ***Chapter 2: Literature review.*** This chapter describes the relevant researches which are useful to compare and improve the proposed research work. It reviews the literatures, which are related to the behaviour of individual structural components and the entire building behaviour in fire incidents. Also some pertinent works on the performance of individual BRB elements and their usage as a braced resisting system in the structural frame under various loading conditions are presented in this chapter.

- ***Chapter 3: Theoretical background (research methodology).*** This chapter focuses on the methods used for accomplishing the main purpose of this thesis. The principal issues, which affect the behaviour of structural components under fire condition, are discussed in this chapter. As an example, the effects of boundary (restraint) conditions and material strength degradation at elevated temperature are pointed out in this chapter. In terms of finding the handy formulations, the basic theories on thermal and structural response of BRB element against fire loading are detailed out. An overall introduction on the existing fire tests used for verifying the accuracy of proposed numerical solutions is presented in this chapter. Moreover, a brief description on the overview of available computer programs used in this study is provided in this chapter.

- ***Chapter 4: Elevated temperature behaviour of BRB sub-element.*** This chapter describes the process of analyses for modelling the BRB individual member under fire condition. The response of BRB constituent components at high temperature is concluded thoroughly in this chapter. The accuracy of proposed numerical analyses presented in this chapter is validated by comparing the FE results with existing analytical formulations and experimental test predictions.

- ***Chapter 5: Influence of BRB system on the response of structural frame at fire.*** This chapter provides a thorough description on the development and validation of the numerical approach, namely, "stiffness reduction technique" proposed for simulating the global collapse in a two dimensional structural plane frame with BRBs, at fire. The influence of BRB system on the prevention of spreading local to global collapse in the structural frame at fire is discussed and compared with that of OCBs. Finally by means of the validated model, the concluding remarks on enhancing the stability of structural frame for preventing the progressive collapse due to fire loading are given at the end of this chapter.

- ***Chapter 6: The effect of BRB system on the fire resistance of entire building.*** This chapter investigates the effect of BRB system on the overall stability and fire resistance of whole building and a thorough comparison on the influence of this system with that of OCBs is provided also in this chapter. The accuracy of numerical model is verified by validating the FE results with the predictions of existing fire tests, carried out on an eight storey structure at Cardington laboratory.

- ***Chapter 7: Conclusions and recommendations.*** This chapter concludes and summarizes the results obtained in the previous chapters and provides recommendations for further future studies.

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